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# CALCULATION OF THE WIDTH OF BARRIER PILLAR REQUIRED TO PROTECT A DEVELOPMENT DRIVAGE AGAINST INUNDATION

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# CALCULATION OF THE WIDTH OF BARRIER PILLAR REQUIRED TO PROTECT A DEVELOPMENT DRIVAGE AGAINST INUNDATION

by

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## SUMMARY

An enquiry by the Cape Breton Development Corporation to the CANMET Coal Research Laboratory as to the dimensions of a barrier pillar required to protect a development entry from inundation by water from abandoned workings lead to an analysis of possible modes of pillar failure, and the resulting stability calculations are presented in this report.

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# NÉCESSITÉ DE DÉTERMINER LA LARGEUR DU PILIER DE LIMITE POUR PROTÉGER LA GALERIE CHASSANTE DE L'INONDATION

par

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## RÉSUMÉ

Pour faire suite à une demande de la Société de développement de Cap Breton portant sur les dimensions du pilier de limite requises afin de protéger une galerie chassante de l'inondation causée par l'eau provenant de sites de travaux abandonnés, le personnel du Laboratoire de recherche sur le charbon de CANMET a effectué une analyse des modes communs de rupture des piliers. Ce rapport présente une analyse du résultat des calculs de stabilité.

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## INTRODUCTION

With respect to safe employment in Cape Breton Development Corporation Coal Mines, the Canada Labour code (Chapter 1011) makes the following provisions regarding barriers against the inundation of workings by water:

> para 112(1) 'Where underground workings in a mine are advancing towards a place containing or likely to contain dangerous accumulation of water or flammable or noxious gases, at least one borehole shall be bored near the centre of the working face to a depth of at least 15 ft. in advance of such working face and at least two boreholes shall be bored near each side of the working face to a depth of at least 10 ft. in advance of such working face, for the purpose of locating the damgerous accumulations of water or gases.'
> para 115(b) 'A solid barrier of unworked mineral of not less than 150 ft. shall be left between the workings of a submarine lease and any other submarine lease.'

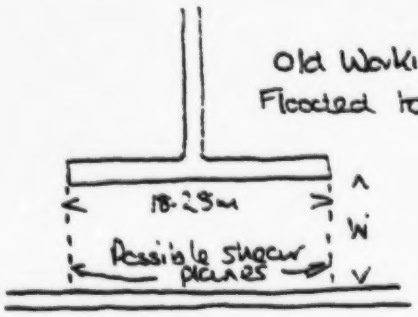
In the United Kingdom, mining legislation requires a 37 m (120 ft) pillar to be left between known abandoned and flooded workings and adjacent working places.

The Cape Breton Development Corporation requested that the CANMET Coal Research Laboratory examine the possible modes of pillar failure in the instance of a development entry paralleled for 18.28 m by an abandoned, flooded development entry in an adjacent colliery in the same seam. In the absence of a detailed plan, a verbal description of the situation given by CBDC has been translated into the diagram shown in Figure 1, and stability calculations made on this basis. The first step in the consideration of the problem was to consider the various failure conditions that could apply.

## MODES OF PILLAR FAILURE

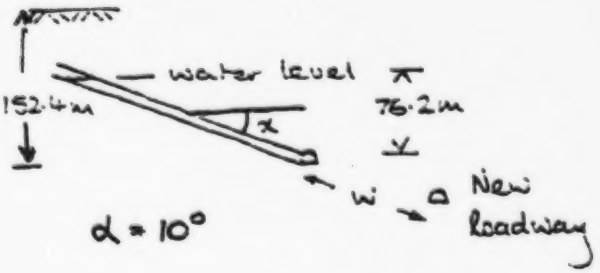
Considering the hypothetical pillar illustrated in Figure 1, there are several possible modes of failure:

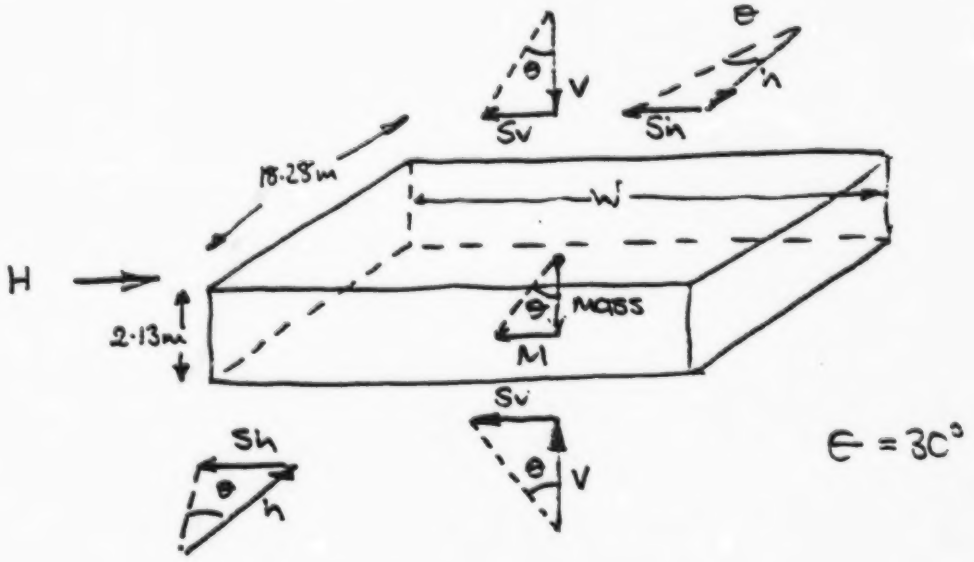
PLAN VIEW OF DEVELOPMENTS




Proposed Development

SECTION THROUGH DEVELOPMENT




Summary of Forces acting on the Coal Pillar / Block

Fig 1 Sketch of In-Situ Coal Pillar/Block as Described by CBEC

a) sliding failure along the roof, floor and sides of the rectangular, isolated coal block, promoted by the force on the flooded side due to the hydraulic head,

b) sliding failure along one, two or three of the proposed failure planes,

c) as a) and b), but assuming the pillar to be saturated, hence giving a pore pressure acting against the forces resisting shear,

d) in the case of stability under the above conditions, the cover load on the pillar may cause pillar failure, and hence inundation,

e) any of the above may infer stability, but the hydraulic conductivity of the coal may be high enough to allow percolation of sufficient quantities of water through the fissures in the pillar to endanger the development workings.

## CALCULATION OF MINIMUM PILLAR WIDTHS

Using information supplied by CBDC, the following minimum pillar widths have been calculated for the case illustrated in Figure 1. Since this diagram may not reflect accurately the in situ structures, and since no factor of safety has been included, the values obtained should definitely not be used as design parameters, rather the method of calculation only should be noted and applied along with safety factors dictated by judgement and the particulars of the situation, to a more detailed version of the underground conditions.

### FAILURE BY SHEAR ON THE ROOF, FLOOR AND SIDES

Using the nomenclature and parameter values illustrated in Figure 1, the minimum pillar width required to prevent failure can be calculated by equating the forces promoting sliding and the forces resisting sliding.

The forces promoting sliding will be the hydraulic head acting on one face of the coal pillar/block, and the component of the mass of the block acting parallel to the shear planes.

The forces resisting sliding can be determined by applying the Mohr-Coulomb failure criterion. The most conservative estimate of pillar requirement will be obtained by assuming pre-existing shear planes as

indicated in Figure 1, in which case the proportion of a normal force, N, resisting sliding will be N tan $\emptyset$, where $\emptyset$ is the residual angle of internal friction. A more realistic estimate may be made by taking into account the cohesive strength of the rock along the sides of the pillar, assuming negligible cohesive strength along the roof and floor parting planes.

If the angle of internal friction of the rock is assumed to be 30°, and the forces acting normal to the shear planes proposed in Fig. 1 are calculated, than the minimum pillar width required can be evaluated from the equilibrium equations. The dip of the seam is small (10°) so the difference between the vertical cover stress and the normal force is small, hence the treatment of the pillar as horizontal structure.

The equilibrium equations for cohesionless and cohesive conditions can therefore be written:

for cohesionless ground:

$$H = 2Sv + M + 2Sh \qquad \text{Eq 1}$$

for cohesive ground:

$$H = 2Sv + M + 2Sh + 2C \qquad \text{Eq 1a}$$

The forces promoting and resisting sliding can be calculated as follows:

The hydraulic head is 76.2 m and acts on an area of 38.94 $m^2$, therefore,

$$H = 76.2 \times 38.94 \times 10^{-3} \text{ MN}$$

$$H = 29.07 \text{ MN} \qquad \text{Eq 2}$$

The mass of the coal block can be determined in terms of W, the pillar/block width, assuming a coal density of 1400 $kg/m^3$, therefore,

$$M = (2.13 \times 18.28 \times W \times 1400 \times 9.8 \times 10^{-6}) \tan 30° \text{ MN}$$

$$M = 0.308W \text{ MN} \qquad \text{Eq 3}$$

The cover load which produces the force Sv can be derived by using the equation,

$$\text{cover load} = \text{depth} \times 0.0255\ MN/m^2$$

therefore, $Sv = (152.4 \times 0.0255 \times 18.28 \times W)\tan 30°\ MN$

$$Sv = 41.01W\ MN \qquad \text{Eq 4}$$

The horizontal rock stress which produces the force Sh can be determined by accepting hydrostatic conditions, or by assuming it to be related to the Poissons Ratio 'v' of the rock by the equation,

$$\sigma h = \sigma v \cdot \frac{v}{1 - v}$$

where $\sigma h$ and $\sigma v$ are the horizontal and vertical rock stresses respectively and $v = 0.2$ then $\sigma h = 0.25\ \sigma v$, therefore,

$$Sh = 0.25\ (.52.4 \times 0.0255) \times 2.13 \times W \times \tan 30\ MN$$

$$Sh = 1.19W\ MN \qquad \text{Eq 5}$$

The cohesion of the coal can be determined graphically using the Mohr-Coulomb convention of representing triaxial test results. Assuming the compressive strength of coal of 17.2 $MN/m^2$ used in a later section, C can be determined as 5 $MN/m^2$. Again, assuming that the relationship between laboratory determined cohesive strength and the in-situ value is the same as that shown by compressive strength, a value of $C = 1.1\ MN/m^2$ is obtained, therefore:

$$C = 1.1 \times 2.13 \times W\ MN$$

$$= 2.34\ W\ MN \qquad \text{Eq 6}$$

Substituting (2),(4),(5) and (6) in equations 1a and 1b, a minimum value of W can be found.

for cohesionless ground;

$$W = 0.343\ m$$

for cohesive ground;

$$W = 0.294\ m$$

FAILURE BY SHEAR ON ONE, TWO OR THREE SIDES

Before considering the stability of the coal pillar/block when undergoing shear on one, two or three sides, the likelihood of shear on any combination of planes must be considered. For no resistance to be offered by a plane to sliding, there must be frictionless contact. In underground conditions, this is unlikely to occur in practise, but one situation could be theorised. Consider a coal pillar/block sitting on a very weak, clayey seatearth. Water from the flooded workings penetrates and weakens the seatearth sufficiently for the coal pillar/block to pentrate, leaving the roof beds bridging the pillar. In this case, there would be frictional resistance to sliding only on the sides of the block, and on the floor if the wet clay offered any frictional resistance.

Considering this situation to be the case, then if frictional resistance is offered by the floor, the equilibrium equation will be;

for cohesionless ground;

$$H = 2Sh + M \qquad \text{Eq 6}$$

for cohesive ground;

$$H = 2Sh + M + 2C \qquad \text{Eq 6a}$$

and if no resistance is offered by the floor then the equilibrum equation will be;

for cohesionless ground;

$$H = 2Sh \qquad \text{Eq 7}$$

for cohesive ground;

$$H = 2Sh + 2C \qquad \text{Eq 7a}$$

These equations can be evaluated for W using the parameters derived above, giving W = 10.18 m (3.94 m) if sliding resistance is offered by the seatearth or W = 12.21 m (4.11 m) if no sliding resistance is offered by the seatearth. Figures in brackets refer to results for cohesive ground.

FAILURE OF A SATURATED PILLAR

If the failure of the pillar/block cannot prevent the percolation of water through the pillar, then an additional factor, the pore water pressure, must be taken into consideration. It will act against the forces normal to the sides of the coal pillar/block, and therefore must be subtracted from the forces. The pore pressure will be equal to the hydraulic head, therefore Uv and Uh, the forces exerted vertically and horizontally by the pore water pressure will be given by,

$$Uv = 18.28 \times W \times 76.2 \times 9.8 \times 10^{-3} \text{ MN}$$
$$Uv = 13.65W \text{ MN} \qquad \text{Eq 8}$$

$$Uh = 2.13 \times W \times 76.2 \times 9.8 \times 10^{-3} \text{ MN}$$
$$Uh = 1.59W \text{ MN} \qquad \text{Eq 9}$$

The reduction in frictional resistance along the shear planes will be Uv tan 30 for horizontal planes and Uh tan 30 for vertical planes, therefore the equilibrium equations (1), (6) and (7) can be rewritten for cohesionless ground as;

$$H = 2(Sv - Uv \tan 30) + M + 2(Sh - Uh \tan 30) \qquad \text{Eq 10}$$

$$H = M + 2(Sh - Uh \tan 30) \qquad \text{Eq 11}$$

$$H = 2(Sh - Uh \tan 30) \qquad \text{Eq 12}$$

A term 2C must be added to the right side of each to give the equilibrium equation for cohesive ground.

Solving each for W using values calculated above gives;

W = 0.44 m (0.404 m) for sliding on four sides
W = 31.12 m (5.25 m) for sliding on three sides
W = 53.42 m (5.56 m) for sliding on two sides

Figures in brackets denote the minimum pillar required in cohesive ground.

FAILURE DUE TO COVER LOAD STRESS

As determined above, the cover stress for the case under consideration will be 0.0255 x 152.4 = 3.88 $MN/m^2$, assuming no interaction from adjacent or overlying workings.

The coal strength has been determined in the laboratory as 17.2 $MN/m^2$. It is assumed that this is for a 50 mm diameter core of height/diameter ratio of 2:1. In this case, the in situ strength can be approximated by the equation;

$$\sigma_c/\sigma_0 = (l_0/l_c)^{\frac{1}{2}}$$

where $\sigma_c$ and $l_c$ are the laboratory determined compressive strength and specimen height, and $\sigma_0$ and $l_0$ are the in situ compressive strength and seam height . In this case, $\sigma_c/\sigma_0 = 4.6$, so the in situ strength of the coal can be approximated as 3.74 $MN/m^2$. As this is less than the cover load of 3.88 $MN/m^2$, then failure of the pillar edge will occur. If a circular roadway in homogenous ground is considered, then the radius of the yield/elastic boundary, r, is given by;[1]

$$\bar{r} = r_0 \frac{[2q - \sigma_0 + p'(k + 1)]^{1}/k - 1}{[(p + p') (k + 1)]} \qquad \text{Eq 13}$$

where $r_0$ is the roadway radius (2.13 m assumed)

q is the in situ hydrostatic stress (3.88 $MN/m^2$)

k is the triaxial stress factor (for $\phi = 30°$, k = 3)

p is the restraint on the roadway side (assumed to be 0.1 $MN/m^2$ i.e. small)

p' is the unconfined strength of failed coal (assumed to be 0.2 $MN/m^2$)

and $\sigma_0$ is the in situ coal strength, 3.74 $MN/m^2$.

Solving the equation, $\bar{r}$ = 2.74 m, i.e. the yield zone width is 2.74 m - 2.13 m or 0.61 m.

The interaction of the elevated stresses induced adjacent to the openings by the openings themselves will set the minimum pillar width. The tangential stress $\sigma_\theta$, in the elastic zone at a point r from the centre of a circular roadway is given by;[1]

$$\sigma_\theta = q + A(r_0/r)^2 \qquad \text{Eq 14}$$

The minimum pillar width will occur when the sum of the stresses induced on the elastic side of the abutment is equal to the abutment stress, $\hat{\sigma}_\theta$ given by;[1]

$$\sigma_\theta = q + A(r_0/r)^2 \qquad \text{Eq 15}$$

Therefore the stability equation will be;

$$2(q + A(r_0/r)^2) = q + A(r_0/r)^2 \qquad \text{Eq 16}$$

The parameter A is given by;[1]

$$A = \frac{[(K-1)q + \sigma_0]}{[(k+1)]} \times \frac{[2q - \sigma_0 + p'(k+1)]^2}{[(p+p')(k+1)]}/k - 1 \qquad \text{Eq 17}$$

Substituting previously obtained values, A = 10.58, equation (16) can now be solved for r:

$$2(3.88 + 10.58(2.13/r)^2 = 3.88 + 10.58(2.13/2.74)^2$$

$$\frac{(2.13)^2}{r} = \frac{10.27/2 - 3.88}{10.58}$$

$$\frac{2.13}{r} = 0.118$$

$$r = 2.13/0.343$$

therefore, $$r = 6.21 \text{ m}$$

Since the value of r is to be measured from roadway centre to roadway centre, the width of the coal pillar required between the two roadways will be 6.2 m - (2 x 2.13), therefore the minimum pillar width W = 1.98 m.

PERCOLATION OF WATER THROUGH THE PILLAR

According to Darcy's Law the rate of flow through a porous medium is:

$$Q = K\ i\ A$$

where Q is the flow in $m^3$/day, K is the hydraulic conductivity (m/day), i is the hydraulic gradient and A is the cross sectional area perpendicular to the flow ($m^2$).

General ranges of K for consolidated materials are:[2]

| | |
|---|---|
| Sandstone | 0.001 - 1 m/day |
| Shale | $10^{-7}$ m/day |
| Dense, solid rock | $10^{-5}$ m/day |
| Fractured or weathered rock | 0.001 - 10 m/day |

If we assume a value for K of 0.001 m/day, then for no flow,

$$W = 0.001 \times 152.4 \times 38.94$$

$$= 5.93 \text{ m}$$

## DISCUSSION

The calculations given above have derived a range of values of the minimum pillar width required. It is obvious that the treatment of the coal as a cohesive material has a marked effect on the pillar width. In the interest of economy, therefore, a more accurate determination of coal shearing properties should be made to facilitate a more accurate calculation. The collection of experimental data to evaluate the other parameters would further enhance the calculations.

It should be noted that all of the calculations are made on the basis of a solid pillar. As the calculations with respect to failure under cover load indicate, a yield zone will be formed. An additional increment of pillar width equal to twice the yield zone width must be added to the selected minimum pillar width to account for this reduction in the solid pillar dimension.

A tentative minimum pillar width from these calculations would therefore be 54.64 m in cohesionless ground or 7.15 m in cohesive ground.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Wilson, A.H. "The stability of underground workings in the soft rocks of coal measures"; International Journal of Mining Engineering, 1983; p. 191-187.

2. Bouwer, H. "Groundwater hydrology"; published: McGraw-Hill 1978; ISBN 0-07-006715-5